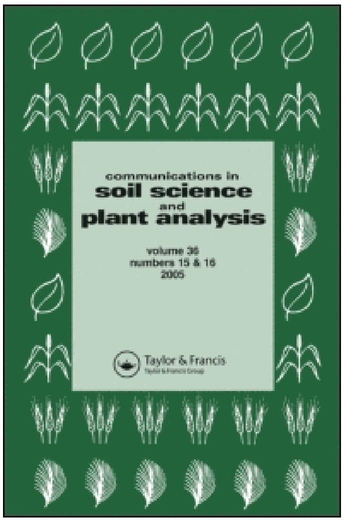

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Role of Cover Crops in Improving Soil and Row Crop Productivity

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Role of Cover Crops in Improving Soil and Row Crop Productivity

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Abstract: Cover crops play an important role in improving productivity of subsequent row crops by improving soil physical, chemical, and biological properties. The objective of this article is to review recent advances in cover crops practice, in the context of potential benefits and drawbacks for annual crop production and sustained soil quality. Desirable attributes of a cover crop are the ability to establish rapidly under less than ideal conditions, provide sufficient dry matter or soil cover, fix atmospheric nitrogen (N), establish a deep root system to facilitate nutrient uptake from lower soil depths, produce organic matter with low-residue carbon/nitrogen (C/N) ratio, and absence of phytoxic or allelopathic effects on subsequent crops. Cover crops can be leguminous or nonleguminous. Leguminous cover crops provide a substantial amount of biologically fixed N to the primary crop, as well as ease of decomposition due to their low C/N ratio. Legume cover crops also possess a strong ability to absorb low available nutrients in the soil profile and can help in increasing concentration of plant nutrients in the surface layers of soil. Some nonleguminous cover crops having high N scavenger capacity compared with leguminous crops and sometimes, the growth of these scavenging grass cover crops is limited by N deficiency, growing grass/legume mixtures appears to be the best strategy in obtaining maximum benefits from cover crops.

Keywords: Biological activities, organic matter, soil quality, sustainable system

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INTRODUCTION

Increasing crop productivity and maintaining a clean environment are major challenges to agricultural scientists in the 21st century. To meet these challenges, crop production practices need to be modified in favor of higher yields and minimized environmental pollution. The management of crop residues is a key component of sustainable cropping systems (Ruffo and Bollero, 2003). Historically, crop residues have played an important role as mulch for soil and water conservation and as an input for maintaining soil organic matter and returning nutrients to soil. To achieve these objectives the use of cover crops in cropping systems is an important strategy. Before discussing cover crops and their role in crop production, it is important to define the term cover crops. Cover crops can be defined as close-growing crops that provide soil protection, and soil improvement between periods of normal crop production, or between trees in orchards and vines in vineyards (SSSA, 1997). Cover crops are grown not for market purposes, but when plowed under and incorporated into the soil, cover crops may be referred to as green manure crops. Cover crops are sometimes called catch crops. In Table 1 are listed important tropical and temperate cover crops. Cover crops are usually killed on the soil surface before they are mature by using appropriate herbicides. In most studies, cover crops managed as no-till mulches have been killed with glyphosate (N-[phosphono-methyl]glycine), paraquat (1,1-dimethyl-4-bipyridinium ion) (Bauer and Reeves, 1999; Raimbault et al., 1990; Reeves et al., 1993; Sarrantonio and Scoot, 1988) or mixture of non-selective, post-emergence and pre-emergence herbicide (Teasdale and Shirley, 1998). Because many growers often want to reduce use of chemical inputs, non-chemical methods of killing or suppressing cover crops are desirable (Creamer and Dabney, 2002). These mechanical methods are mowing, rolling, roll-chopping, undercutting, and partial rototilling. Creamer and Dabney (2002) have reviewed literature on killing cover crops mechanically.

Cover crops are generally included in cropping systems as nutrient management tools (Ruffo and Bollero, 2003). Cover crops can be leguminous or nonleguminous. Legume cover crops are used as a source of nitrogen (N) for the following cash crop (Smith et al., 1987) while grasses are mainly used to reduce NO_3 leaching and erosion (Meisinger et al., 1991). Biological N fixation by leguminous crops offers potential to reduce the need for N fertilizers for the succeeding crop (Singh et al., 2004). A bicultural of a legume and a grass is used with the intention of providing both benefits simultaneously (Ranells and Wagger, 1996).

The benefit from legume cover crops in crop rotation has long been recognized and believed to be mainly attributed to N contribution to subsequent crops (Smith et al., 1987). In recent years, economic and environmental considerations have renewed interest in this old practice for improving crop productivity and soil health and maintaining sustainability of agroecosystems.

Table 1. Major cover crops of tropical and temperate regions

Tropical region		Temperate region	
Common name	Scientific name	Common name	Scientific name
Sunnhemp	*Crotalaria juncea* L.	Hairy vetch	*Vicia villosa* Roth
Sesbania	*Sesbania aculeata* Retz Poir	Barrel medic	*Medicago truncatula* Gaertn
Sesbania	*Sesbania rostrata* Bremek & Oberm	Alfafa	*Medicago sativa* L.
Cowpea	*Vigna unguiculata* L. Walp.	Black lentil	*Lens culinaris* Medikus
Soybean	*Glycine max* L. Merr.	Red clover	*Trifolium pratense* L.
Clusterbean	*Cyamopsis tetragonoloba*	Soybean	*Glycine max* L. Merr.
Alfalfa	*Medicago sativa* L.	Faba bean	*Vicia faba* L.
Egyptian clover	*Trifoliam alexandrium* L.	Crimson clover	*Trifolium incarnatum* L.
Wild indigo	*Indigofera tinctoria* L.	Ladino clover	*Trifolium repens* L.
Pigeon pea	*Cajanus cajan* L. Millspaugh	Subterranean clover	*Trifolium subterraneum* L.
Mungbean	*Vigna radiata* L. Wilczek	Common vetch	*Vicia sativa* L.
Lablab	*Lablab purpureus* L.	Purple vetch	*Vicia benghalensis* L.
Graybean	*Mucuna cinerecum* L.	Cura clover	*Trifolium ambiguum* Bieb.
Buffalobean	*Mucuna aterrima* L. Piper & Tracy	Sweet clover	*Melilotus officinalis* L.
Crotolaria		Winter pea	*Pisum sativum* L.
Breviflora	*Crotolaria breviflora*		
White lupin	*Lupinaus albus* L.	Narrowleaf vetch	*Vicia angustifolia* L.
Milk vetch	*Astragalus sinicus* L.	Milk vetch	*Artragalus sinicus* L.
Crotalaria	*Crotalaria striata*		
Zornia	*Zornia latifolia*		
Jackbean	*Canavalia ensiformis* L. DC.		
Tropical kudzu	*Pueraria phaseoloides* (Roxb.) Benth.		
Velvetbean	*Mucuna deeringiana* Bort. Merr.		
Adzuki bean	*Vigna angularis*		
Brazilian stylo	*Stylosanthes guianiensis*		
Jumbiebean	*Leucaena leucocephala* Lam. De Wit		
Desmodium	*Desmodiumovalifolium* Guillemin & Perrottet		
Pueraria	*Pueraria phaseoloides* Roxb.		

The objective if this review is to compile information on beneficial effects and drawbacks of cover crops on soil health, and crop yield.

BENEFITS OF COVER CROPS

Planting cover crops before or between main crops as well as between trees or shrubs of plantation crops can improve soil physical, chemical, and biological properties and consequently lead to improved soil health and yield of principal crops. Leaving cover crops as surface mulches in no-till crop production systems has the advantage of increasing nitrogen economy (Smith et al., 1987; Frye et al., 1988; Sustainable Agriculture Network, 1998) conserving soil moisture (Morse, 1993), reducing soil erosion (Langdale et al., 1991), improving soil physical properties (Blevins and Frye, 1993), increasing nutrient retention (Staver and Brinsfield, 1998; Dinnes et al., 2002), increasing soil fertility (Cavigelli and Thien, 2003), suppressing weeds (Creamer and Baldwin, 2000; Creamer et al., 1996a), reducing diseases and insects (Sustainable Agriculture Network, 1998; Ristaino et al., 1996), reducing global warming potential (Robertson et al., 2000), and increasing crop yields (Triplett et al., 1996). These various beneficial effects of cover crops on soil management and crop productivity are discussed in the following sections.

Nitrogen Economy

The contribution of N is the most commonly observed primary benefit of leguminous crops (Singh et al., 1992). Both legume and nonlegume cover crops affect N fertilizer management (Bauer and Roof, 2004). Legume cover crops fix atmospheric N and reduce N fertilizer needs for succeeding cash crops (Hoyt and Hargrove, 1986; Reeves, 1994). The rate of N fixed by cover crops is determined largely by the genetic potential of the legume species and by the amount of plant available N in the soil. Data in Table 2 show quantities of nitrogen fixed by different legume cover crops. Two bacterial species, i.e., *Rhizobium* and *Bradyrhizobium* are responsible for symbiotic nitrogen fixation in legumes. The genus *Rhizobium* contains fast growing, acid-producing bacteria, while the *Bradyrhizobium* are slow growers that do not produce acid (Brady and Weil, 2002). Soil factors such as pH, moisture content, and temperature also determine N fixation capacity of a legume cover crop. In some cases, the amount of N provided by legume cover crops is adequate to produce optimal yields of subsequent non-leguminous crops; however, higher N requiring cereals such as corn (*Zea mays* L.) generally need supplemental N fertilizer. In such crops N fertilizer rates could be lowered appreciably while maintaining optimal economic yields (Frye et al., 1988). Table 3 shows data relating dry matter production and N uptake by different cover crops. Dry matter yields and N uptake values

Table 2. Quantity of nitrogen fixed by legume cover crops

Crop species	N_2 Fixed (kg ha^{-1} crop^{-1})	References
Peanut (*Arachis hypogaea* L.)	40–80	Brady and Weil (2002)
Cowpea (*Vigna unguiculata* L. Walp.)	30–50	Brady and Weil (2002)
Alfalfa (*Medicago sativa* L.)	78–222	Heichel (1987)
Soybean (*Glycine max* L.)	50–150	Brady and Weil (2002)
Fava bean (*Vicia faba* L.)	177–250	Heichel (1987)
Hairy vetch (*Vicia villosa* Roth.)	50–100	Brady and Weil (2002)
Ladino clover (*Trifolium repens* L.)	164–187	Heichel (1987)
Red clover (*Trifolium pratense* L.)	68–113	Heichel (1987)
White lupine (*Lupinus albus* L.)	50–100	Brady and Weil (2002)
Field peas (*Pisum sativum* L.)	174–195	Heichel (1987)
Chickpea (*Cicer arietinum* L.)	24–84	Heichel (1987)
Pigeon pea (*Cajnus cajan* L. Huth.)	150–280	Brady and Weil (2002)
Kudzu (*Pueraria phaseoloides* Roxb. Benth)	100–140	Brady and Weil (2002)
Chick pea (*Cicer arietinum* L.)	24–84	Heichel (1987)
Greengram (*Vigna radiata* L. Wilczek.)	71–112	Chapman and Myers (1987)
Lentil (*Lens culinaris* L.)	57–111	Smith et al. (1987)

provide an indication of N uptake capacity of a cover crop from residual soil inorganic N and mineralized soil organic N as well as biological fixed N in the case of a legume cover crop. Data in Table 3 show that most legume crops have a high capacity to accumulate N in their dry matter. Similarly, rye (*Secale cereale* L.) as a cereal also accumulated 100 kg N ha^{-1}. Table 4 provides data of nitrogen fertilizer equivalence (NFE) of legume cover

Table 3. Dry matter yield and N uptake by cover crops

Crop species	Dry matter yield (Mg ha^{-1})	N uptake (kg ha^{-1})
Hairy vetch	5.1	209
Bigflower vetch	1.9	60
Crimson clover	2.4	56
Berseem clover	1.5	45
Australian winter pea	1.6	68
Common vetch	4.3	134
Subterranean clover	4.0	114
Rye	6.3	100
Wheat	1.5	29

Source: Compiled from Frye et al. (1988).

Table 4. Nitrogen fertilizer equivalence (NFE) of legume cover crops to succeeding nonlegume crops

Legume/non-legume crop	NFE ($kg\,ha^{-1}$)
Hairy vetch/cotton	67–101
Hairy vetch + rye/corn	56–112
Hairy vetch/corn	78
Hairy vetch/sorghum	89
Hairy vetch/corn	78
Hairy vetch + wheat/corn	56
Crimson clover/cotton	34–67
Crimson clover/corn	50
Crimson clover/sorghum	19–128
Common vetch/sorghum	30–83
Bigflower vetch/corn	50
Subterranean clover/sorghum	12–103
Sesbani/allowland rice	50
Alfalfa/corn	62
Alfalfa/wheat	20–70
Arachis spps/wheat	28
Subterranean clover/wheat	66
White lupin/wheat	22–182
Arachis spps/corn	60
Pigeon pea/corn	38–49
Sesbania/potato	48
Mungbean/potato	34–148
Chickpea/wheat	15–65

Source: Compiled from Smith et al. (1987) and Kumar and Goh (2000).

crops to succeeding non-legume crops. The NFE values varied from 12 to 182 $kg\,ha^{-1}$. Smith et al. (1987) reported that NFE values range from 40 to 200 $kg\,ha^{-1}$, but more typically are between 75 to 100 $kg\,ha^{-1}$. Interseeding red clover (*Trifolium pretense* L.) into small grains is a common practice in the northeastern United States (Singer and Cox, 1998), and such practice can provide up to 85 $kg\,N\,ha^{-1}$ to the subsequent corn crop (Vyn et al., 1999). Researchers in the southeastern United States have estimated that legumes such as hairy vetch can supply well over 100 $kg\,N\,ha^{-1}$ to following corn or grain sorghum crops (Blevins et al., 1990; Hargrove, 1986; Oyer and Touchton, 1990; Wagger, 1989). On prairie soils in Kansas, Sweeney and Moyer (2004) found that grain sorghum following initial kill-down of red clover and hairy vetch yielded as much as 131% more than continuous sorghum with estimated fertilizer N equivalencies exceeding 135 $kg\,ha^{-1}$.

Legume cover crops should be inoculated with an appropriate strain of N fixing bacteria. Perennial legumes fix N during any time of active growth. In annual legumes, N fixation peaks at flowering. With seed formation, it ceases and the nodules fall off the roots. Rhizobia return to the soil environment to await their next encounter with legume roots. These bacteria remain viable in the soil for 3 to 5 years, but often at too low a level to provide significant optimal N-fixation capacity when legume is replanted (Sustainable Agriculture Network, 1998).

The effectiveness of various types of cover crops or combinations of cover crop species on soil N availability and the productivity of succeeding crops has been extensively evaluated (Smith et al., 1987; Holderbaum et al., 1990; Kuo et al., 1996; Clark et al., 1997; Kuo and Jellum, 2002).

In addition to fixing N, cover crops have been reported to reduce the potential for NO_3 leaching from farm fields (Owens, 1990; Brandi-Dohrn et al., 1997; Staver and Brinsfield, 1998). In studies reviewed by Meisinger et al. (1991), cover crops reduced both the mass of N leached and NO_3 concentration of leachate by 20 to 80% compared with no cover crop control. They also determined that grasses and brassicas were two to three times as effective as legumes in reducing NO_3 leaching. Francis et al. (1998), Shepherd (1999), and Rasse et al. (2000) reported that incorporating a nonleguminous cover crop in a cropping system has reduced NO_3^- leaching because the cover crop can reduce water percolation and also effectively use NO_3^- that would otherwise leach.

Cover crops accumulate inorganic soil N between main crop seasons, and holding it in an organic form, prevent it from leaching. The N is subsequently released to the next crop as the cover crop residue decomposes (Dinnes et al., 2002). Rye (*Secale cereale* L.), a cereal, is recognized as having great potential as a scavenger of residual inorganic N present after corn harvest (Staver and Brinsfield, 1990; Ditch and Alley, 1991; McCracken et al., 1994). McCracken et al. (1994) reported that rye was much more effective than vetch (*Vicia villosa* Roth) in reducing NO_3^- leaching. Furthermore, effective erosion control (Kessavalou and Walters, 1997), reduced soil compaction (Raper et al., 2000b), and suppressed weed emergence (Blum et al., 1997) by use of rye in field cropping systems have been reported. The higher capacity of rye in scavenging residual N compared to vetch was associated with its more rapid establishment of an extensive root system (McCracken et al., 1994).

Increasing Organic Matter Content

The importance of soil organic matter in improving soil fertility and productivity is well known (Allison, 1973; Bauer and Black, 1994; Wilhelm et al., 2004). Soil organic matter stabilizes soil aggregates, makes soil easier to cultivate, increases aeration, and increases soil water holding and buffering capacities; soil organic matter breakdown releases available nutrients to plants (Carter and Stewart, 1996). The soil organic matter content depends on soil type (Schimel et al., 1994), frequency and type of cultivation (Heenan et al., 1995), cropping and residue management (Grace et al., 1995; Webb et al., 2003), and fertilizer N input (Bhogal et al., 1997).

Soil structural degradation is common in intensively cultivated ecosystems due to the depletion of soil organic matter (Grandy et al., 2002). Elliott (1986) reported that aggregate stability decreased in cultivated land compared with native grassland, and that decreases in soil organic matter content paralleled the decrease in stability. Organic matter in agricultural soils contributes positively to soil fertility, soil tilth, crop production, and overall soil sustainability (Bauer and Black, 1994; Reeves, 1997). Cover crops supply organic matter to the soil by decomposing their residues. Data in Table 5 show that legume cover crops increased both the soil organic carbon and organic nitrogen relative to fallow and nonlegume cover crops.

Continued crop production potentials of soils are directly related to their organic matter contents (Lal, 1998; Mann et al., 2002). Within limits, crop productivity is positively related to the soil organic matter content (Reicosky and Forcella, 1998). Soil organic matter improves soil physical, chemical, and biological properties and consequently crop yields (Doran et al., 1998; Doran, 2002; Franzluebbers, 2002). The primary physical characteristics influenced by soil organic matter are those associated with soil structure soil aggregation and aggregate stability (Six et al., 1999). Soil organic matter compounds bind the primary soil particles in the aggregate, physically and chemically, and this, in turn, increases the stability of the aggregates and limits their breakdown during the wetting process (Emerson, 1997; Golchin et al., 1995; Lado and Ben-Hur, 2004). In turn, aggregates and their stability have tremendous influences on infiltration of water, soil water holding capacity, and aeration as well as mass bulk density and penetration resistance (Carter, 2002).

Table 5. Soil organic carbon and nitrogen in 0–7.5 cm depth as affected by cover crops in a no-tillage system

Crop species	Organic carbon ($g\,kg^{-1}$)	Organic nitrogen ($g\,kg^{-1}$)
Fallow	7.9b[a]	0.58c
Hairy vetch	9.7a	0.80ab
Crimson clover	8.4b	0.65bc
Subterranean clover	10.0a	0.81a
Common vetch	10.2a	0.63c
Rye	8.7b	0.65bc

[a]Values followed by same letter in the same column are not significantly different ($P < 0.05$).

Source: Adapted from Hargrove (1986).

Chemical properties influenced by soil organic matter content are soil pH, nutrient availability and cycling, cation exchange capacity, and buffering capacity (Tisdall et al., 1986). Organic matter can also bind and detoxify potentially toxic cations [aluminum (Al), manganese (Mn)]. Although a large proportion of the total soil N remains physically and chemically protected from microbial degradation in the stable soil organic matter pool, and thus is unavailable for immediate plant uptake, more labile fractions of soil organic matter, which are generally much smaller, remain an important source of N (Jenkinson and Parry, 1989). In addition, cover crop residue buffers soil against the forces of raindrop impact and wind shear. Crop residues on the soil surface influence radiation balance and energy fluxes and reduce the rate of evaporation from the soil (Wilhelm et al., 2004). Furthermore, increasing C and N storage in soil using management practices, such as cover cropping may also help to reduce the deleterious effects of global warming by increased sequestration of atmospheric CO_2 and N (Lal and Kimble, 1997; Paustian et al., 1997; Post and Kwon, 2000; Sainju et al., 2002).

Soil organic carbon is one of the most important terrestrial pools for carbon storage and exchange with atmospheric CO_2 (Follett, 2001). With land cultivation the soil organic carbon is exposed to oxidation and lost as atmospheric CO_2. This process decreases soil organic carbon. Increasing or maintaining soil C, the basic constituent of soil organic matter, is an important objective for the sustainable use of soil resources (Lal and Kimble, 1997). Appropriate soil and crop management practices such as conservation tillage, use of cover crops, and efficient use of nutrients and water can improve or maintain soil organic carbon. In Table 6 data are presented for carbon sequestration under different management practices.

Enriching the Soil with Essential Mineral Nutrients

In addition to N, cover crops supply other essential nutrients to subsequent crops, when their tissues decompose. Legumes explore subsoil nutrient pools and capture available nutrients through their extensive root systems (Gathumbi et al., 2003). The enrichment of soil with essential nutrients varied with cover crop, especially with quantity of dry matter produced and concentration of nutrients in the dry tissues. Biomass production of cover crops is also affected by environmental conditions, soil fertility and crop management practices. Furthermore, the enrichment of soil with nutrients is mostly dependent on rooting depths, because the desired action lies in the relative transfer to the plow layer of nutrients found only deeper in the horizons. Rooting depth is not only determined by type of crop but more importantly by soil depth, presence of plow pans, aeration, soil texture, soil fertility, disease, and presence of toxic elements. Table 7 shows nutrient accumulation by a mucuna (*Mucuna cinerecum*) cover crop grown on a Brazilian Inceptisol.

Table 6. Soil and crop management practices associated with carbon sequestration in the United States

Management practice	Carbon sequestration (MMTC yr^{-1})[a]
Crop rotation and cover crops	5.1–15.3
Conservation reserve program (CRP)	8.8–13.3
Conservation tillage	17.8–35.7
Crop residue/biomass management	11–67
Fallow reduction	1.4–2.7
Fertilizer management	6–18
Livestock manure	3.6–9.0
Supplemental irrigation	1.0–3.2
Total	54.7–164.2
Average	109.4

[a]MMTC = Million metric tons of carbon.
Source: Adapted from Follett (2001).

Cover crops have been reported to improve P uptake of succeeding crops (Cavigelli and Thien, 2003). The improved P uptake of succeeding cover crops is associated with several mechanisms. Residues of cover crops may convert relatively unavailable native and residual fertilizer P to chemical forms more available to succeeding crops. Alfalfa (*Medicago sativa* L.), red clover (*Trifolium pratense* L.), sweet clover (*Melilotus officinalis* L.), and

Table 7. Dry matter yield and nutrient accumulation in a nintyone days old mucuna (graybean) green manure crop grown on an inceptisols of central Brazil

Dry matter yield/nutrient	Value[a]
Dry matter (kg ha^{-1})	7016
N (kg ha^{-1})	185
P (kg ha^{-1})	12
K (kg ha^{-1})	161
Ca (kg ha^{-1})	73
Mg (kg ha^{-1})	19
Zn (g ha^{-1})	229
Cu (g ha^{-1})	170
Mn (g ha^{-1})	1668
Fe (g ha^{-1})	2528

[a]Values are averages of two field experiments conducted for two consecutive years.
Source: Fageria (unpublished data).

lupine (*Lupinus albus* L.) can absorb more P than most other crops from soils testing low in phosphorus (P) (Gardner et al., 1983; Braum and Helmke, 1995). On decomposition, organic P in the cover crop tissues could provide a relatively labile form of P to succeeding crops (Tiessen et al., 1994). The, residue decomposing process may improve P availability to succeeding crops by releasing CO_2, which forms H_2CO_3 in the soil solution, resulting in the dissolution of primary P-containing minerals (Sharpley and Smith, 1989). In soils with high P-fixing capacities, organic compounds released during decomposition processes may increase P availability by blocking P-adsorption sites (Easterwood and Sartain, 1990) and complex excess Al in acidic soils.

Improving Soil Structure

Soil structure is defined as the combination or arrangement of primary soil particles into secondary units or peds (SSSA, 1997). Soil structure is important in describing the health of agricultural soils (Fageria, 2002). Soil structure is important for water infiltration, aeration and plant root development. Improvement of soil structure or aggregation by the action of living and decaying cover crop tissue is widely reported (Lynch and Bragg, 1985; Boyle et al., 1989; Haynes et al., 1991; Haynes and Francis, 1993). Karlen et al. (1994) reported a significant soil aggregation improvement in corn planted in a no-till system with crop residues compared with crop residues removed. Miller and Dick (1995) reported that cover crops provide greater root activity and C inputs which improve soil aggregation and maintain higher organic C pools compared with conventionally managed (fallow) soil.

Improvement in soil hydraulic conductivity and infiltration by modifying soil structure, aggregate stability and macropores have been reported by Murphy et al. (1993) and Kumar and Goh (2000) by crop residues retained on the soil surface. Similarly, up to eightfold increase in hydraulic conductivity in zero-tillage stubble retained have been reported over treatments where stubble was removed by burning (Valzano et al., 1997). Cassel et al. 1995) reported that tillage practices that leave crop residues on the soil surface can reduce or eliminate surface crusting, increase infiltration, and reduce surface runoff and soil loss while increasing crop yields. Baumhardt and Lascano (1996) reported significant improvement in infiltration rate with crop residues left on soil compared with bare soil.

Reducing Soil Erosion

Loss of topsoil by wind and water erosion caused by poor soil management is by far the largest single factor contributing to deterioration of soil physical, chemical, and biological properties and to the further decline in productivity of most crop lands (Pierce and Lal, 1994; Fageria et al., 1997; Dabney et al., 2001). Soil erosion removes the top soil layer, which generally contains large amounts of soil organic matter and immobile nutrients. The loss of such top soil layers ultimately reduces crop production. The magnitude of the effect of erosion on yields also varies among soils, crops, and management practices (Lal, 1987).

When the soil surface is exposed to raindrop impact, the permeability of the soils is reduced by seal formation (Morin et al., 1981; Ben-Hur and Letey, 1989). The seal formation reduces the infiltration rate, thus increasing runoff (Morin et al., 1981), and may increase soil loss (Ben-Hur et al., 1992). Reduction in soil erosion by cover crops is associated with increasing in soil organic matter content which improve soil water infiltration and holding capacity. With more infiltration and less runoff from each rainfall event, soil erosion is significantly reduced. Cover crops growing after soybean increased surface cover, and anchor residue, and reduced rill erosion (Kaspar et al., 2001).

Increasing Soil Biological Activity

Soil biological properties are intimately related to the chemical environment in the soil and are important in controlling soil tilth as soil chemical and physical properties (Brye et al., 2004). Soil microorganisms play a crucial role in maintaining soil quality due to their action in nutrient cycling through the decomposition of organic matter and nutrient storage (Turco et al., 1994). Cover crops may provide favorable environmental conditions (moisture, temperature, availability of carbon) for the proliferation of soil microorganisms. The soil microbial biomass is the living component of the soil that comprises mainly bacteria and fungi, including soil microfauna and algae (Kumar and Goh, 2000). Although it accounts for only 1 to 3% of organic C and 2 to 6% of organic N in soil (Jenkinson, 1987), it plays a key role in soil organic matter and nutrient dynamics by acting as both a sink (during immobilization) and as a source (mineralization) of plant nutrients (Kumar and Goh, 2000). Several workers have reported higher microbial biomass in no-till than in conventionally tilled soils (Linn and Doran, 1984; Buchanan and King, 1993; Angers et al., 1993; Ndiaye et al., 2000; Schutter and Dick, 2001). Furthermore, higher populations of bacteria, actinomycetes, fungi, earthworms, and nematodes have been reported in residue mulch than in incorporated residues (McCalla, 1958). In addition to the residue management practice, residue quality affects microbial population, fewer bacteria, and fungal populations were reported on grass/cereal residues than in legume residues (Kumar and Goh, 2000; Tian et al., 1993).

Cover crops may also exert a significant effect on soil vesicular-arbuscular mycorrhiza (VAM). The VAM fungal infection increases in corn after cover cropping (Boswell et al., 1998; Kabir and Koide, 2000), whereas no effect or even slight negative effects were shown in small grain cereals (Baltruschat and Dehne, 1989). Cover crops may also influence the degradation potential of the soil for pesticides (Thorup-Kristensen et al., 2003). Bottomley et al. (1999) found increased degradation of the herbicide 2,4-D in both surface and subsoil layers after a rye cover crop compared to no cover crop in a vegetable cropping system.

Conserving Soil Moisture

Conserving soil moisture with cover crop residues is widely reported (Smith et al., 1987; Sustainable Agriculture Network, 1998). Cover crops residues left on soil improve infiltration of rain water and also reduce evaporative losses, resulting in less moisture stress during drought periods. Grass type cover crops such as rye, barley, wheat, and sorghum-sudangrass have been reported to be very effective in soil moisture conservation (Sustainable Agriculture Network, 1998). Gallaher (1977) showed that soil remained wetter and crop yields were higher when rye was left as surface mulch than when aboveground parts of the rye were removed in a conservation tillage system. Daniel et al. (1999) reported that rye had the highest biomass of several cover crop species tested and soil had higher water contents under rye. The greatest differences in water contents between mulched and bare soils can be expected during short dry periods (7–14 days), not longer ones (Smith et al., 1987).

Suppressing Weeds

Cover crops control weeds and consequently reduce use of herbicides. Weed suppression by cover crops can be due to shading, competition for nutrients and water (Creamer et al., 1996b; Martin, 1996; Liebman and Davis, 2000). Cover crops displace weeds while they grow and their residues can further suppress weeds (Hoffman et al., 1996; Smeada and Weller, 1996; Moyer et al., 2000). Weed control is usually best from dense cover crop plantings and further, when cover crops are allowed to grow for the longest time possible (Smeada and Putnam, 1988). Rye residues are among the most effective mulches and have been reported to suppress weed growth for up to 6 weeks after rye desiccation (Putnam et al., 1983). Nelson et al. (1991) reported less weed biomass with an annual clover (*Trifolium incarnatum* L.) than with two perennial clovers [*Trifolium pretense* L., *Trifolium repens* L. (red and white)] used as spring cover crops. Similarly, Ross et al. (2001) reported that seven clover species suppressed weed biomass but varied from species to species and management practices. Brandsaeter and Netland (1999) reported that weed suppression is one of the several benefits achieved by including a cover crop in a cropping system.

Decreasing Disease and Insect Problems

The benefits of cover crops in controlling diseases and insects may be associated with breaking pest cycles by growing cover crops between main crops. Cover crops have been reported to be responsible for creating a favorable environment for beneficial predators and parasitoid insects, which control harmful insects (Sustainable Agriculture Network, 1998). Similarly, preceding cover crops have been reported to control many soil-borne pathogenic fungal diseases and nematodes in succeeding cash crops (Sustainable Agriculture Network, 1998).

Improving Yields of Subsequent Crops

Improvements in soil physical, chemical, and biological environment by cover crops are known to improve yields of subsequent crops. Increases in crop yields vary from crop to crop and agroecological regions. Furthermore, yield increases depend on management of cover crops as well as subsequent crops. Agronomically, significant N yield responses of cereals following grain legumes compared with cereal monoculture are frequently measured (Chalk, 1998). The positive N response of the subsequently grown cereal has been attributed to the transfer of biologically fixed N, to N sparing under the antecedent legume, and to less immobilization of nitrate during the decomposition of legume residues (Chalk, 1998). Higher corn yield was achieved following white clover (*Trifolium repens* L.) (7.2 $\mathrm{Mg\,ha^{-1}}$) and red clover (*Trifolium pretense* L.) (6.7 $\mathrm{Mg\,ha^{-1}}$) cover crops than following no cover crops (5.7 $\mathrm{Mg\,ha^{-1}}$) (Hively and Cox, 2001). Peoples and Herridge (1990) reported that responses in grain yield of cereals to previous crops of tropical grain legumes varied from $+0.20$ to $+3.68\,\mathrm{t\,ha^{-1}}$ compared with cereal-cereal monocrop yields with relative increases being in the range 16 to 353%. Improvement in cotton yield in conservation tillage cropping systems has been reported (Bauer and Busscher, 1996; Raper et al., 2000a; Bauer and Roof, 2004).

Several studies have verified that the amount of N in the soil is the key factor in the response of cereals following legumes compared with cereals following nonlegumes (Rowland et al., 1988; Evans et al., 1991; Chalk et al., 1993). However, the response in grain yield may not be entirely due to the amount of available soil N. Improvement in soil structure, the breaking of insects and diseases cycles which afflict cereal monoculture, and phytotoxic and allelopathic effects of different crop residues have all been implicated in the yield response (Chalk, 1998; Peoples and Herridge, 1990). In Table 8 data are presented to show influence of cover crops on yields of corn, sorghum, and cotton after fallow and cover crops. These data indicate that the legumes cover crops provide yield-influencing benefits compared with a fallow/cash crop cropping system.

DISADVANTAGES OF COVER CROPS

There are no known major disadvantages of cover crops. However, concern has been raised over potential harmful effects of cover crops to the succeeding crop (Karlen and Doran, 1991; Johnson et al., 1998). Cover crop may create N deficiency for the next crop if too much N is immobilized and not released in a timely manner (Vyn et al., 1999). Karlen and Doran (1991) showed that cover crops before corn created an early season N deficiency, and even additional N fertilizer did not make up the difference. Similarly, Martinez and Guiraud (1990), Francis et al. (1998), and Wyland et al. (1995) reported that high C/N ratio cover crops may reduce yield of succeeding cash crops because of N immobilization. It is often stated that net N immobilization is likely to occur following addition of plant material with a C/N ratio above 25 (Paul and Clark, 1989).

Rye has been used successfully as a cover crop in the U.S.-northern corn and soybean belt (Dinnes et al., 2002). However, rye should not be grown to maturity as a cover crop because it can reduce the yield of subsequent crops by

Table 8. Yield of corn, sorghum and cotton followed by cover crops. Values are averages across several nitrogen rates and conventional and no-tillage planting systems

Cropping system	Yield of cash crop (Mg ha^{-1})	References
Fallow/corn	5.3	Utomo (1986)
Hairy vetch/corn	7.2	Utomo (1986)
Fallow/corn	3.0	Herbek et al. (1987)
Hairy vetch/corn	4.5	Herbek et al. (1987)
Bigflower vetch/corn	4.5	Herbek et al. (1987)
Fallow/corn	5.3	Ebelhar et al. (1984)
Hairy vetch/corn	7.5	Ebelhar et al. (1984)
Bigflower vetch/corn	5.8	Ebelhar et al. (1984)
Crimson clover/corn	5.8	Ebelhar et al. (1984)
Fallow/corn	5.8	Mitchell and Teel (1977)
Rye/hairy vetch/corn	7.1	Mitchell and Teel (1977)
Rye/corn	5.7	Mitchell and Teel (1977)
Fallow/corn	3.7	Adams et al. (1970)
Hairy vetch/corn	5.5	Adams et al. (1970)
Fallow/sorghum	3.4	Hargrove (1986)
Hairy vetch/sorghum	3.9	Hargrove (1986)
Common vetch/sorghum	3.8	Hargrove (1986)
Crimson clover/sorghum	4.1	Hargrove (1986)
Subterranean clover/sorghum	3.9	Hargrove (1986)
Fallow/cotton	0.72	Touchton et al. (1984)
Common vetch/cotton	0.88	Touchton et al. (1984)
Crimson clover/cotton	0.81	Touchton et al. (1984)

using too much water in the spring or immobilizing large amounts of soil N (Tollenaar et al., 1993). Thelen et al. (2004) reported that moisture stress from the interseeded rye was a predominate factor in soybean grain yield reduction. Other studies have shown that a rye cover crop may reduce subsequent corn yields because of allelopathic effects (Raimbault et al., 1990), or N immobilization under low N conditions (Ebelhar et al., 1984; Blevins et al., 1990). Further research may identify rye genotypes that do not release these compounds (Dinnes et al., 2002).

Overall, growing a cover crop rarely causes pest problems. But certain cover crops occasionally may contribute to particular pest, disease, or nematode problems in localized areas, for example by serving as an alternate host to the pest (Sustainable Agriculture Network, 1998). These negative effects of cover crops apply to specific conditions and can be balanced against positive effects that are discussed in the preceding sections.

CONCLUSIONS

In recent years the importance of cover crops in crop production is increasing due to concern for improving soil quality and reducing chemical inputs. Cover crops can provide numerous benefits related to improving soil fertility, structure, water retention, and groundwater quality and reducing soil erosion, and improving pest management. Selecting the right cover crop is critical to successful cover cropping. Furthermore, as with cash crops, cover crops should be rotated periodically to avoid the build-up of plant-specific pests. With proper selection, use, and management of cover crops, it is possible to improve productivity and also could contribute to improved soil, water, and environmental quality.

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